US012270935B2

(12) **United States Patent**
Tapia

(10) **Patent No.:** **US 12,270,935 B2**
(45) **Date of Patent:** **Apr. 8, 2025**

(54) **MULTI-SENSOR RADAR MICRODOPPLER HOLOGRAPHY**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 376 days.

(21) Appl. No.: **17/713,853**

(22) Filed: **Apr. 5, 2022**

(65) **Prior Publication Data**

US 2023/0314559 A1 Oct. 5, 2023

(51) **Int. Cl.**

G01S 7/295	(2006.01)
G01S 7/40	(2006.01)
G01S 13/50	(2006.01)
G01S 13/931	(2020.01)

(52) **U.S. Cl.**

CPC ***G01S 7/295*** (2013.01); ***G01S 7/40*** (2013.01); ***G01S 13/50*** (2013.01); ***G01S 13/931*** (2013.01)

(58) **Field of Classification Search**

CPC . G01S 7/295; G01S 7/40; G01S 13/50; G01S 13/931; G01S 7/2955; G01S 13/4454; G01S 13/589; G01S 13/87; G01S 13/89; G01S 7/356; G01S 7/415

See application file for complete search history.

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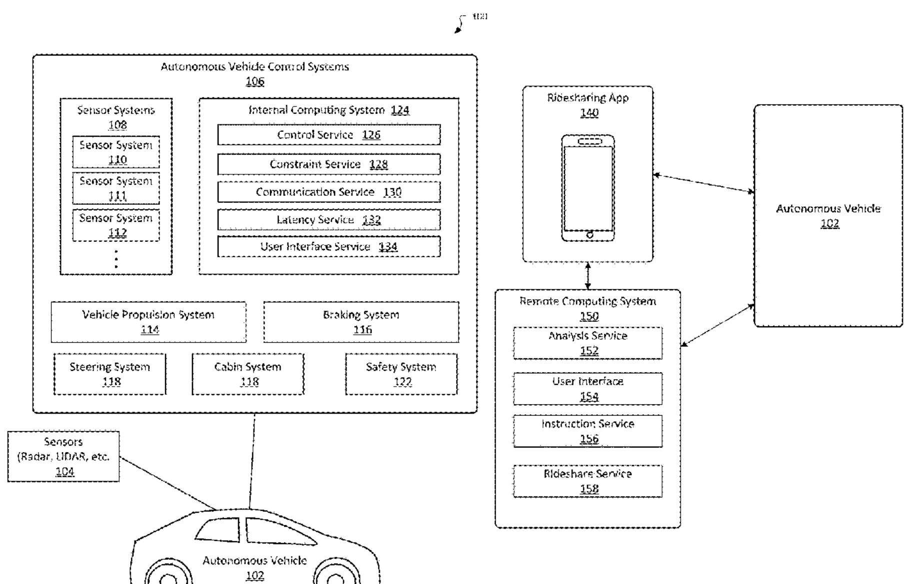
Assistant Examiner — Yonghong Li

(57) **ABSTRACT**

Multi-sensor radar microDoppler holography is described. An example of a method includes performing a 2D Fourier transform calculation for multiple sets of raw Radar sensor data to generate Doppler spatial frequency map data, the raw sensor data including at least a first set of raw sensor data associated with a first Radar sensor at a first location and a second set of raw sensor data associated with a second Radar sensor at a second, different location; performing a DWT calculation of the Doppler spatial frequency map data; applying phase compensation to generate phase compensated data transforms; adding the phase compensated data transforms to generate a sum; performing an inverse 2D Fourier transform calculation to generate a transform result; and extracting microDoppler information and Doppler information extraction from the transform result.

7 Claims, 9 Drawing Sheets



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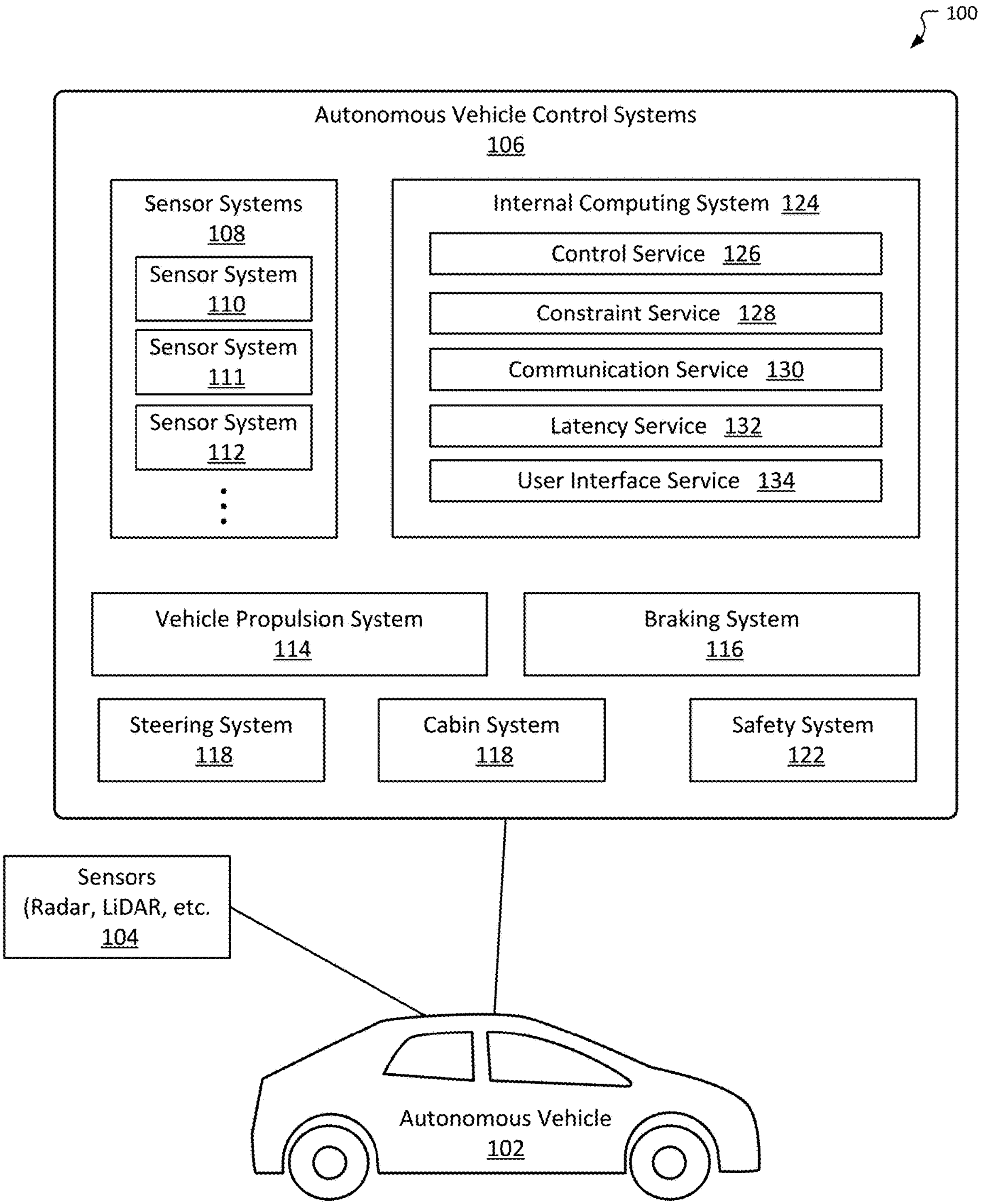
100
Autonomous Vehicle Control Systems
106
Sensor Systems
108
Sensor System
110
Sensor System
111
Sensor System
112
Internal Computing System 124
Control Service 126
Constraint Service 128
Communication Service 130
Latency Service 132
User Interface Service 134
Vehicle Propulsion System
114
Braking System
116
Steering System
118
Cabin System
118
Safety System
122
Sensors
(Radar, LiDAR, etc.
104
Autonomous Vehicle
102

FIG. 1A

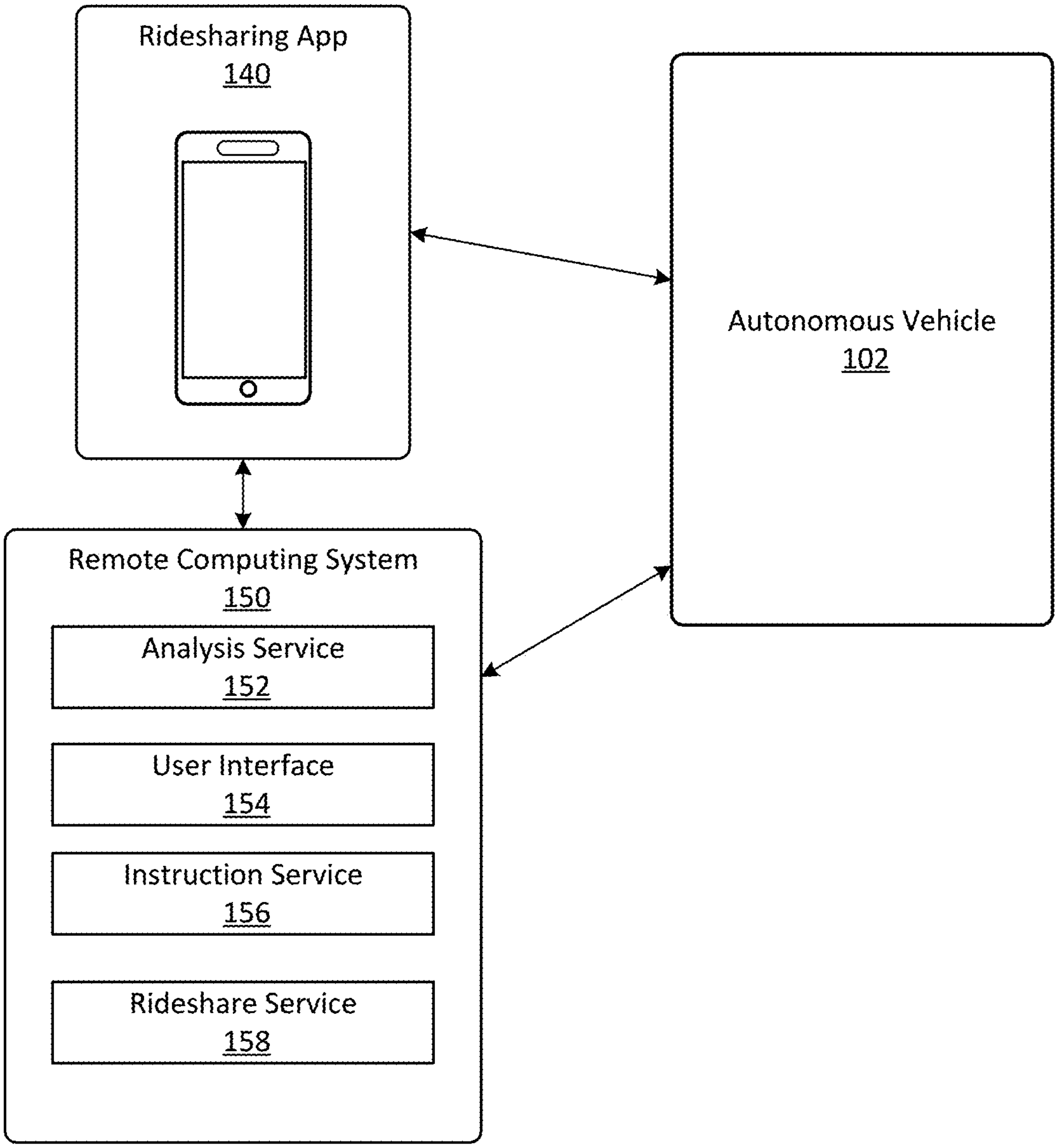
Ridesharing App
140
Autonomous Vehicle
102
Remote Computing System
150
Analysis Service
152
User Interface
154
Instruction Service
156
Rideshare Service
158

FIG. 1B

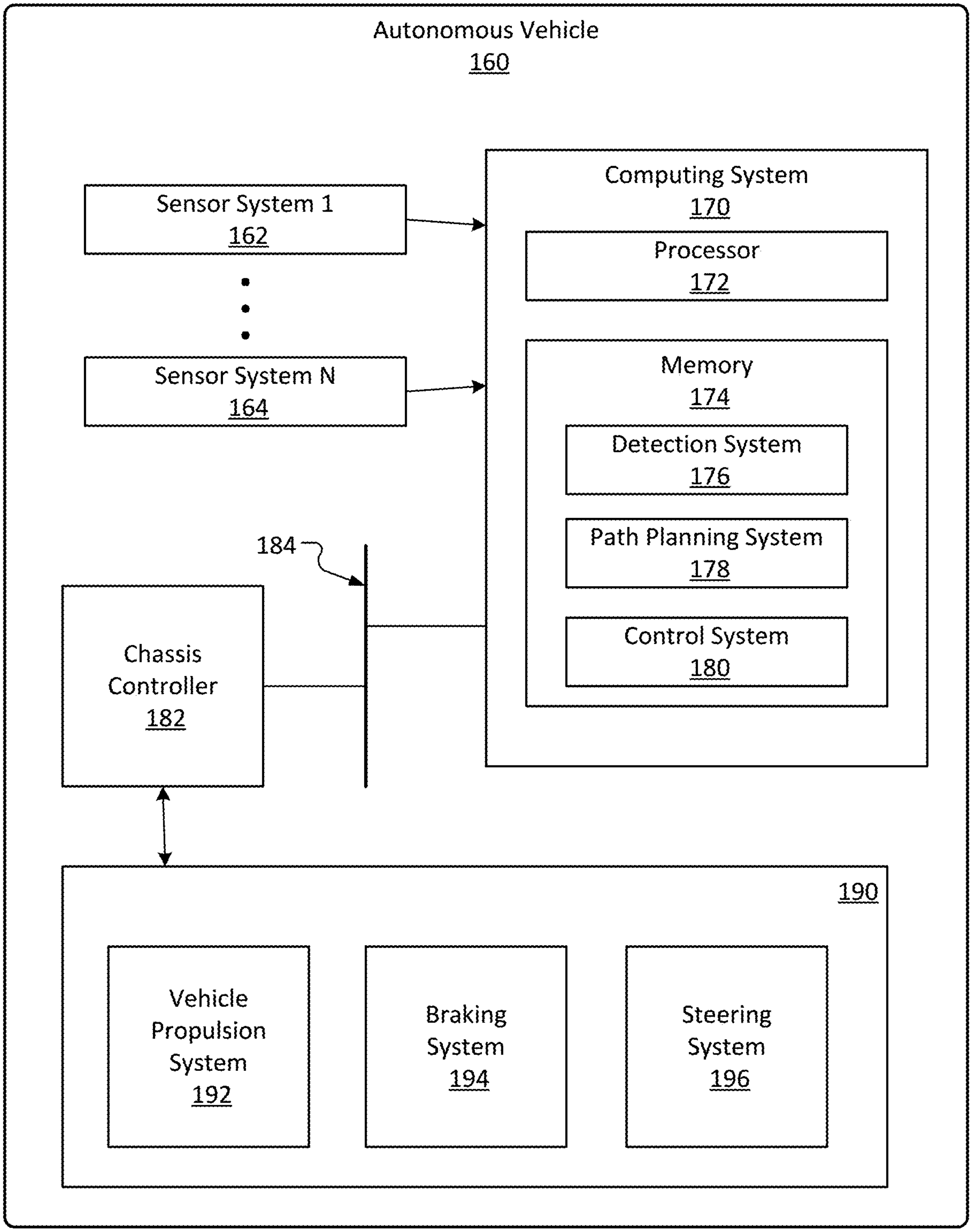
Autonomous Vehicle
160
Sensor System 1
162
Sensor System N
164
Computing System
170
Processor
172
Memory
174
Detection System
176
Path Planning System
178
Control System
180
184
Chassis
Controller
182
190
Vehicle
Propulsion
System
192
Braking
System
194
Steering
System
196

FIG. 1C

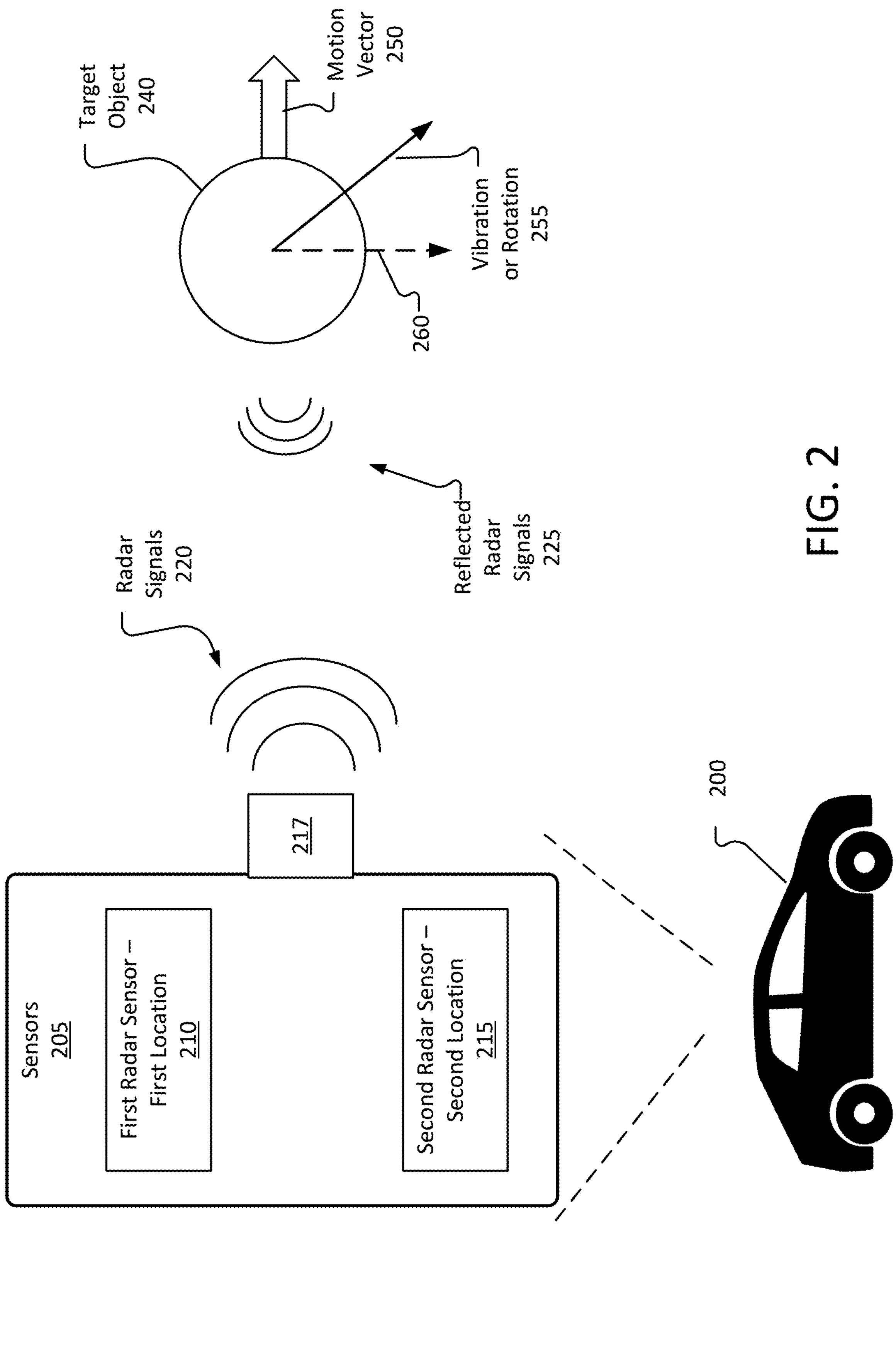
Target Object 240
Motion Vector 250
Vibration or Rotation 255
260
Radar Signals 220
Reflected Radar Signals 225
217
Sensors 205
First Radar Sensor – First Location 210
Second Radar Sensor – Second Location 215
200

FIG. 2

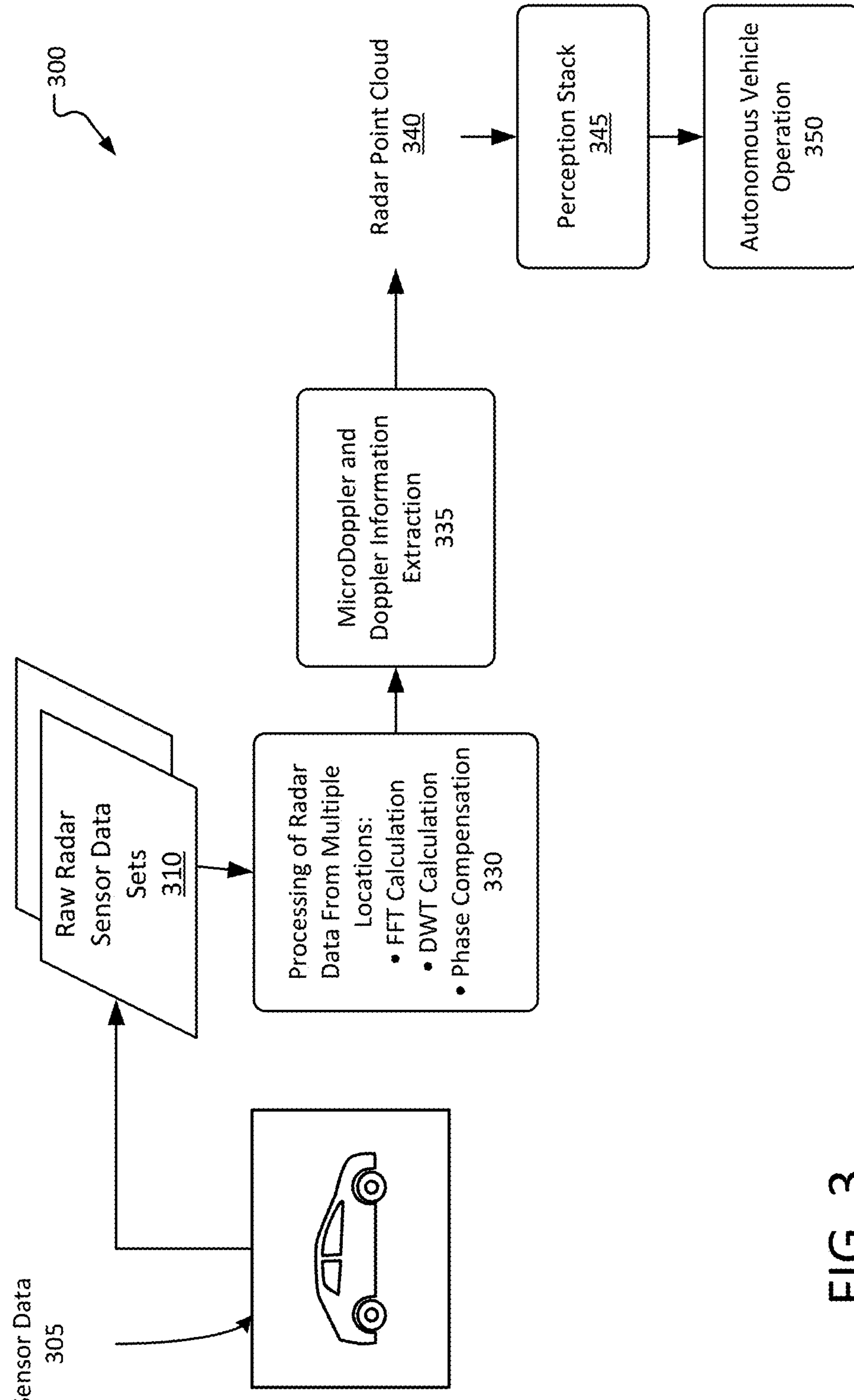
300
Sensor Data
305
Raw Radar
Sensor Data
Sets
310
Processing of Radar
Data From Multiple
Locations:
• FFT Calculation
• DWT Calculation
• Phase Compensation
330
MicroDoppler and
Doppler Information
Extraction
335
Radar Point Cloud
340
Perception Stack
345
Autonomous Vehicle
Operation
350

FIG. 3

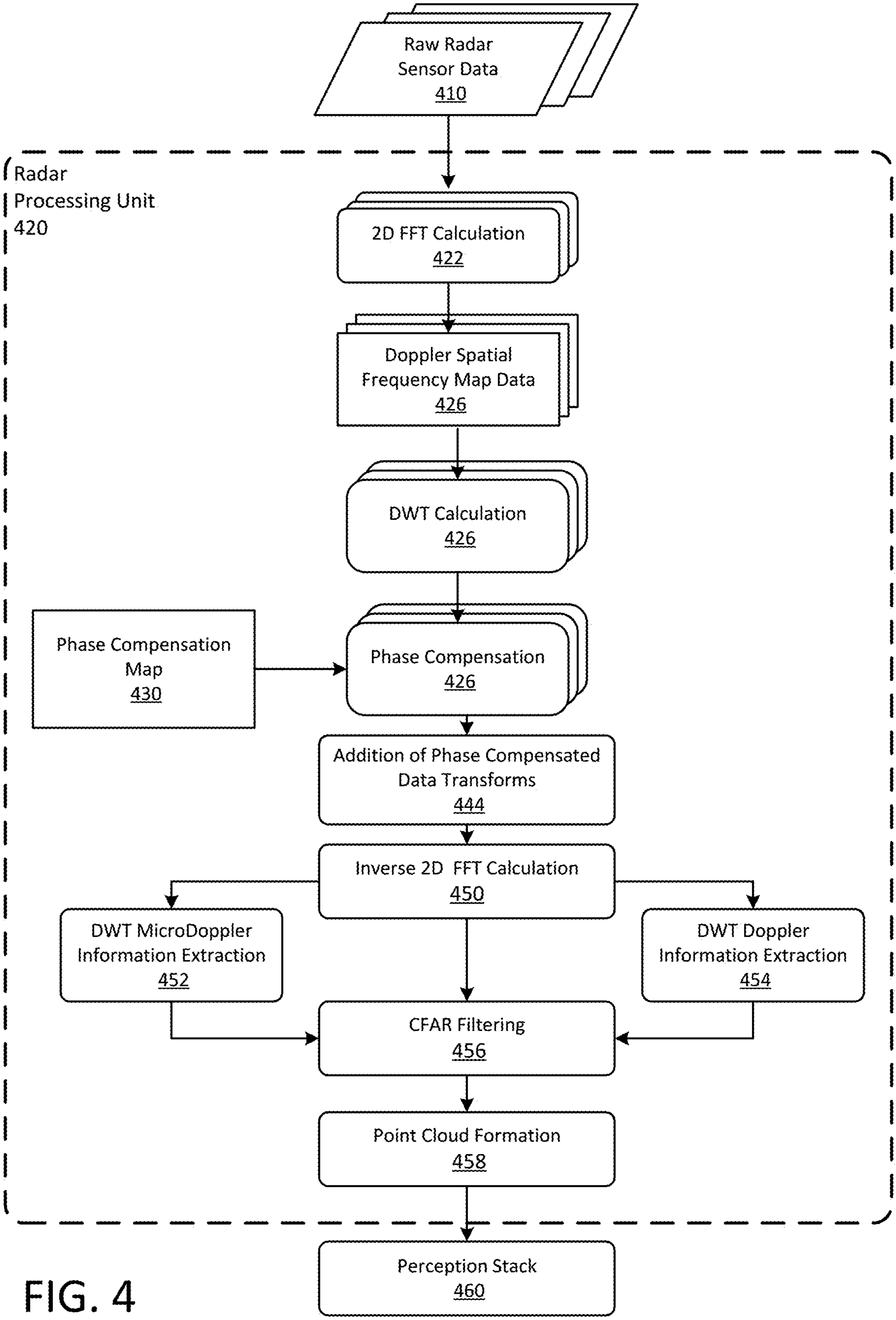
Raw Radar Sensor Data 410
Radar Processing Unit 420
2D FFT Calculation 422
Doppler Spatial Frequency Map Data 426
DWT Calculation 426
Phase Compensation Map 430
Phase Compensation 426
Addition of Phase Compensated Data Transforms 444
Inverse 2D FFT Calculation 450
DWT MicroDoppler Information Extraction 452
DWT Doppler Information Extraction 454
CFAR Filtering 456
Point Cloud Formation 458
Perception Stack 460

FIG. 4

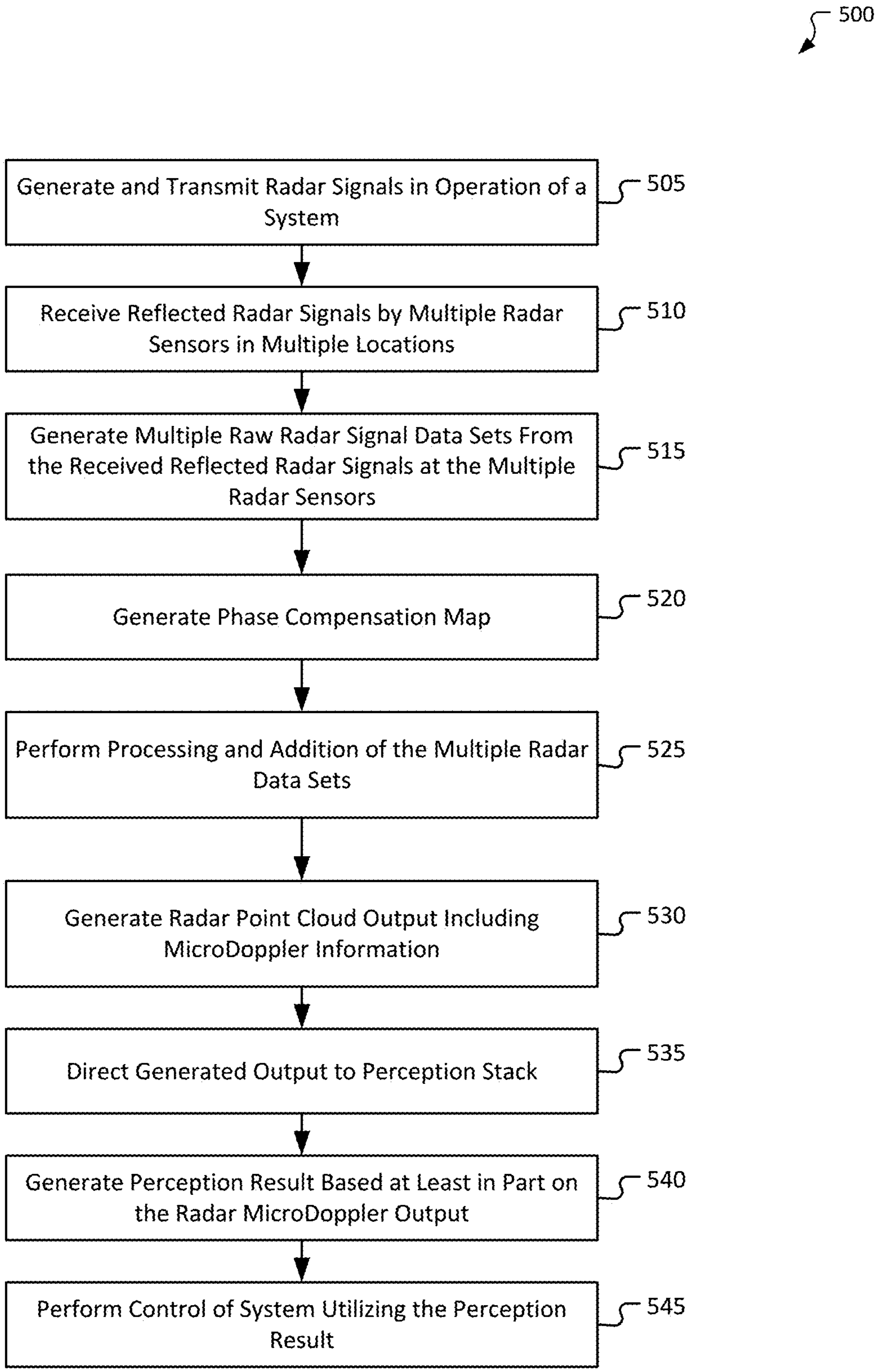
500
Generate and Transmit Radar Signals in Operation of a System
505
Receive Reflected Radar Signals by Multiple Radar Sensors in Multiple Locations
510
Generate Multiple Raw Radar Signal Data Sets From the Received Reflected Radar Signals at the Multiple Radar Sensors
515
Generate Phase Compensation Map
520
Perform Processing and Addition of the Multiple Radar Data Sets
525
Generate Radar Point Cloud Output Including MicroDoppler Information
530
Direct Generated Output to Perception Stack
535
Generate Perception Result Based at Least in Part on the Radar MicroDoppler Output
540
Perform Control of System Utilizing the Perception Result
545

FIG. 5

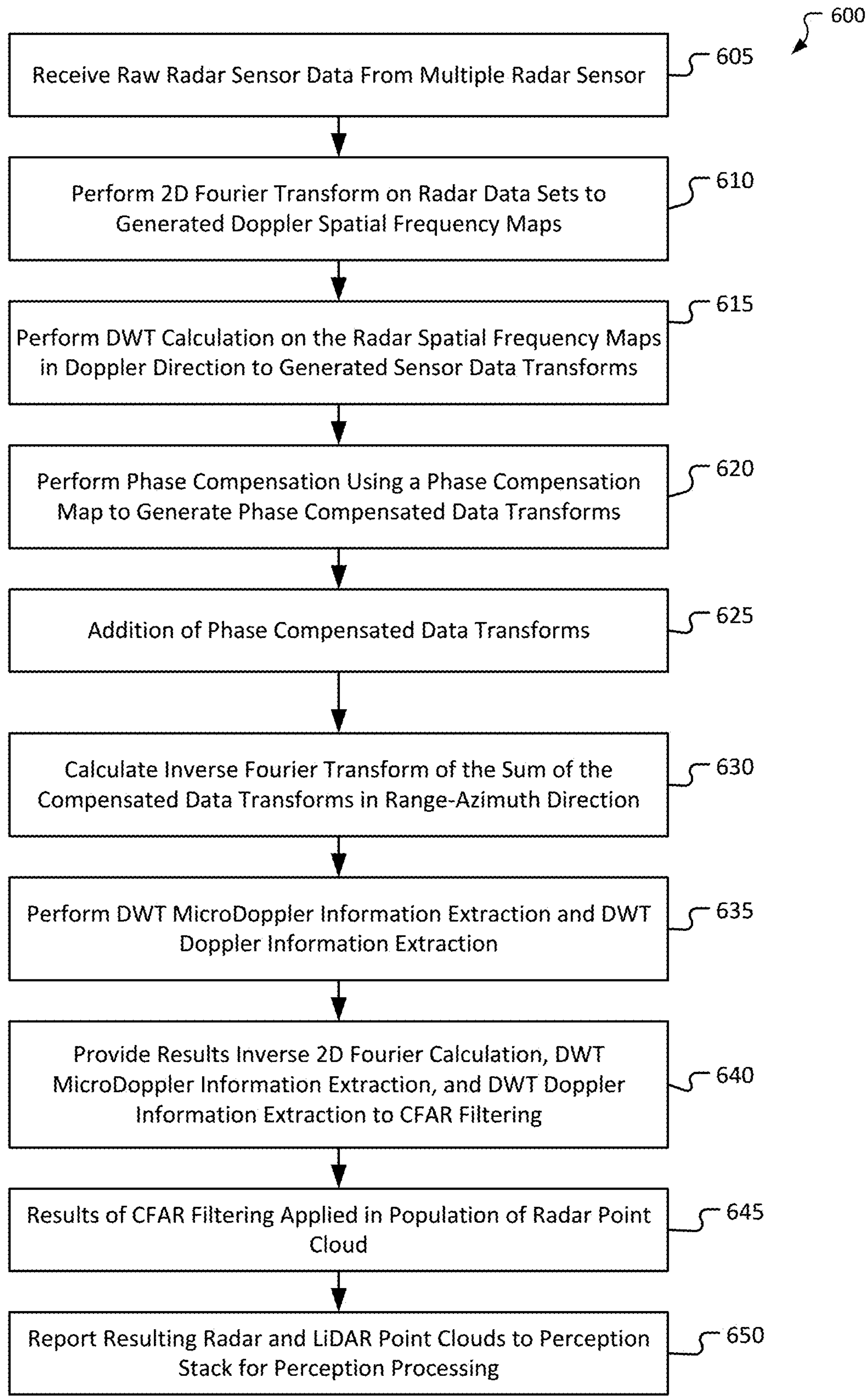
600
Receive Raw Radar Sensor Data From Multiple Radar Sensor
605
Perform 2D Fourier Transform on Radar Data Sets to Generated Doppler Spatial Frequency Maps
610
Perform DWT Calculation on the Radar Spatial Frequency Maps in Doppler Direction to Generated Sensor Data Transforms
615
Perform Phase Compensation Using a Phase Compensation Map to Generate Phase Compensated Data Transforms
620
Addition of Phase Compensated Data Transforms
625
Calculate Inverse Fourier Transform of the Sum of the Compensated Data Transforms in Range-Azimuth Direction
630
Perform DWT MicroDoppler Information Extraction and DWT Doppler Information Extraction
635
Provide Results Inverse 2D Fourier Calculation, DWT MicroDoppler Information Extraction, and DWT Doppler Information Extraction to CFAR Filtering
640
Results of CFAR Filtering Applied in Population of Radar Point Cloud
645
Report Resulting Radar and LiDAR Point Clouds to Perception Stack for Perception Processing
650

FIG. 6

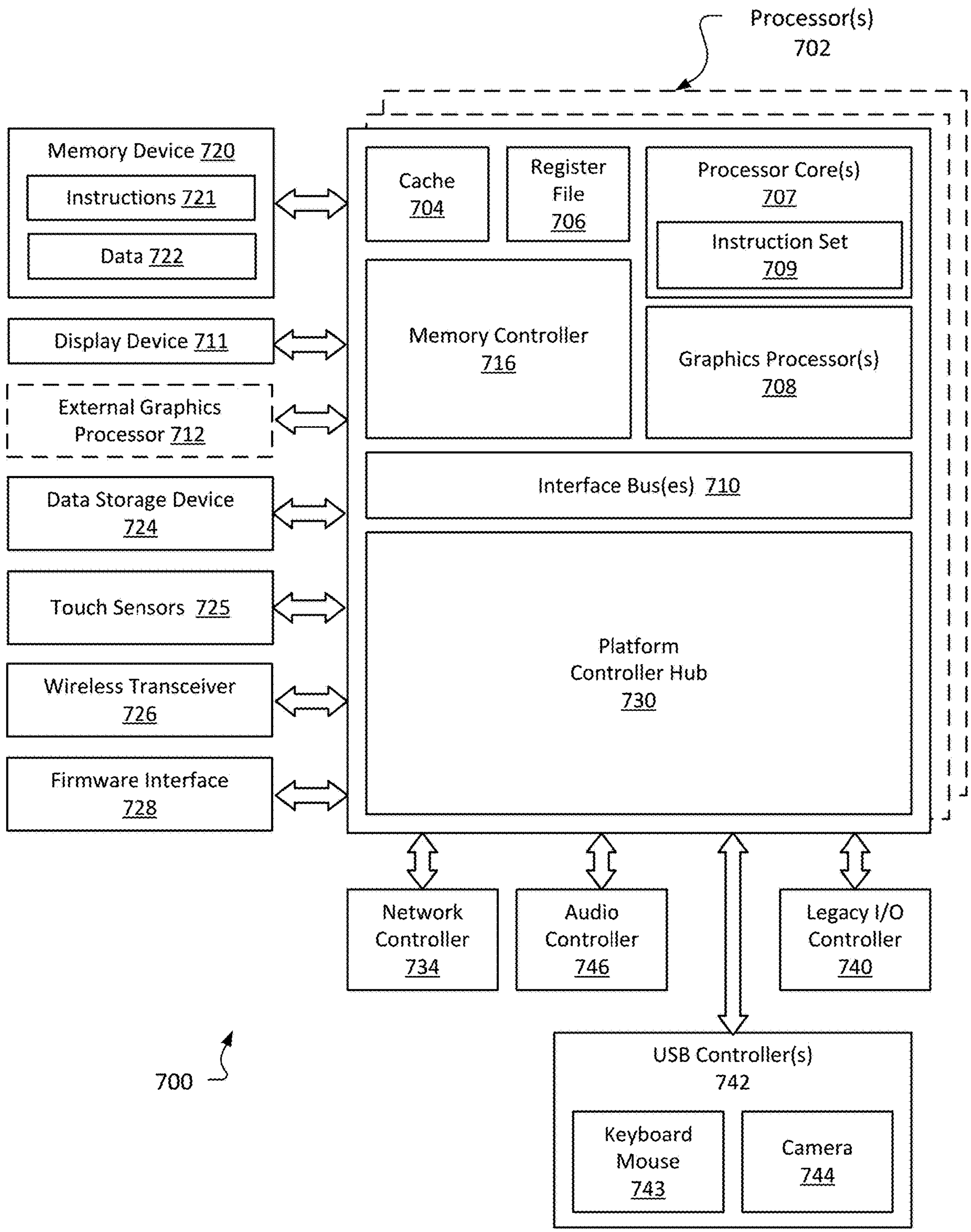
Processor(s)
702
Memory Device 720
Instructions 721
Data 722
Display Device 711
External Graphics Processor 712
Data Storage Device 724
Touch Sensors 725
Wireless Transceiver 726
Firmware Interface 728
Cache 704
Register File 706
Processor Core(s) 707
Instruction Set 709
Memory Controller 716
Graphics Processor(s) 708
Interface Bus(es) 710
Platform Controller Hub 730
Network Controller 734
Audio Controller 746
Legacy I/O Controller 740
USB Controller(s) 742
Keyboard Mouse 743
Camera 744
700

FIG. 7

MULTI-SENSOR RADAR MICRODOPPLER HOLOGRAPHY

FIELD

This disclosure relates generally to the field of data processing and, more particularly, to multi-sensor radar microDoppler holography.

BACKGROUND

Autonomous vehicles, also known as self-driving cars, driverless vehicles, and robotic vehicles, may be vehicles that use multiple sensors to sense the environment and move without human input. Automation technology in the autonomous vehicles may enable the vehicles to drive on roadways and to accurately and quickly perceive the vehicle's environment, including obstacles, signs, and traffic lights. Autonomous technology may utilize map data that can include geographical information and semantic objects (such as parking spots, lane boundaries, intersections, crosswalks, stop signs, traffic lights) for facilitating driving safety. The vehicles can be used to pick up passengers and drive the passengers to selected destinations. The vehicles can also be used to pick up packages and/or other goods and deliver the packages and/or goods to selected destinations.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments described here are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings in which like reference numerals refer to similar elements.

FIGS. **1**A-**1**C are block diagrams to illustrate example autonomous vehicles;

FIG. **2** illustrates Radar sensor operation for microDoppler detection, according to some embodiments;

FIG. **3** is an illustration of multi-sensor radar microDoppler holography, according to some embodiments;

FIG. **4** illustrates multi-sensor Radar data processing, according to some embodiments;

FIG. **5** is a flowchart to illustrate a process for multi-sensor radar microDoppler holography, according to some embodiments;

FIG. **6** is a flowchart to illustrate a process for multiple Radar sensor data processing, according to some embodiments; and

FIG. **7** illustrates an embodiment of an exemplary computing architecture for multi-sensor radar microDoppler holography, according to some embodiments.

DETAILED DESCRIPTION

Embodiments described herein are directed to multi-sensor radar microDoppler holography.

In autonomous vehicle operation and other mobile implementations, distance measurements may be received from multiple distance measurement sensors, wherein the distance sensors may include Radar (Radio Detection and Ranging) and LiDAR (Light Detection and Ranging), among others. Three-dimensional (3D) point clouds may be generated based on the distance measurements. In some cases, 3D point clouds corresponding to distance measurements from different distance measurement sensors may be combined into one 3D point cloud. A model may be generated based on the 3D point cloud. An object may be detected within the model, and in some cases may be classified by

object type. For example, an autonomous vehicle may then navigate its driving by establishing a route that avoids or otherwise takes into consideration the detected object.

In sensing operations for vehicle operations, Frequency Modulated Continuous Waveforms (FMCW) provide high performance processing for automotive radar sensors, and increasingly are also used in automotive LiDAR sensors. FMCW radar is a type of radar sensor radiates continuous transmission power, as with Continuous Wave Radar (CW Radar). However, in contrast to this CW radar, FMCW radar can change its operating frequency during the measurement, i.e., the transmission signal is modulated in frequency.

Due to their highly adjustable nature, FMCW sensors are able to provide an excellent amount of information regarding targets in a scene, both in terms of location and velocity. In addition, FMCW sensors may be used to extract micro-Doppler information about a target. When a radar transmits a signal to a target, the signal interacts with the target, and returns (is reflected back) to the radar. When the target moves with a constant velocity, the carrier frequency of the returned signal will be shifted, which is referred to as the Doppler effect. The Doppler frequency shift is determined by the wavelength of the electromagnetic wave and the relative velocity between the radar and the target.

However, if the target in question includes vibration or rotation in addition to motion, this can induce a frequency modulation on the returned signal, which is referred to as the micro-Doppler effect. The micro-Doppler effect is a signal feature that can provide additional information about target rotational and vibrational motion. For example, the micro-Doppler effect can be applied to help distinguish a living organism (for example, as a dog or other animal) from an inanimate object (such as fire hydrant) that is of similar size, to distinguish between objects in operational and non-operational states, or to otherwise add to ranging information.

MicroDoppler signatures generated using current processing chains includes certain shortcomings. These microDoppler signatures are limited to motion information in a radial direction, and thus providing only limited information if the vibrational or rotational motion of the target is not within this direction. Further, the microDoppler signatures are conventionally limited to using co-located receiver locations, which results in non-optimal information use in platforms having more than one radar sensor. However, fusing microDoppler signatures from two or more different aspect angles from a target is not a trivial process as the alignment of the signal phases and proper combination can be extremely computationally expensive.

In some embodiments, a system or apparatus provides for multi-sensor Radar microDoppler holography, wherein Radar microDoppler holography refers to three-dimensional (3D) Radar imaging including microDoppler information. A system or apparatus includes a processing chain that takes advantage of rotational and vibrational motion vectors by using microDoppler signatures from different sensors at different locations. The system or apparatus applies a custom holographic approach to coherently combine the phase information from different radar sensors to generate micro-Doppler motion vectors of the different point cloud vectors.

FIGS. **1**A-**1**C are block diagrams to illustrate example autonomous vehicles. In FIG. **1**A, autonomous vehicle **102** has the functionality to navigate roads without a human driver by utilizing sensors **104** and autonomous vehicle control systems **106**.

Autonomous vehicle **102** can include, for example, sensor systems **108** including any number of sensor systems (e.g., sensor system **110**, sensor system **112**). Sensor systems **108** can include various types of sensors that can be arranged throughout autonomous vehicle **102**. For example, sensor system **110** can be a camera sensor system. As another example, sensor system **111** can be a light detection and ranging (LIDAR) sensor system. As another example, sensor systems **112** can be a radio detection and ranging (Radar) sensor system, As a further examples, the sensor systems **108** may include an electromagnetic detection and ranging (EmDAR) sensor system, a sound navigation and ranging (SONAR) sensor system, a sound detection and ranging (SODAR) sensor system, a global navigation satellite system (GNSS) receiver system, a global positioning system (GPS) receiver system, accelerometers, gyroscopes, inertial measurement unit (IMU) systems, infrared sensor systems, laser rangefinder systems, microphones, etc.

Autonomous vehicle **102** can further include mechanical systems to control and manage motion of the autonomous vehicle **102**. For example, the mechanical systems can include a vehicle propulsion system **114**, a braking system **116**, a steering system **118**, a cabin system **120** and a safety system **122**. Vehicle propulsion system **114** can include, for example, an electric motor, an internal combustion engine, or both. Braking system **116** can include an engine brake, brake pads, actuators, and/or other components to control deceleration of autonomous vehicle **102**. Steering system **118** can include components that control the direction of autonomous vehicle **102**. Cabin system **120** can include, for example, a cabin temperature control systems, an in-cabin infotainment systems, and other internal elements.

Safety system **122** can include various lights, signal indicators, airbags, systems that detect and react to other vehicles. Safety system **122** can include one or more Radar systems. Autonomous vehicle **102** can utilize different types of Radar systems, for example, long-range Radar (LRR), mid-range Radar (MRR) and/or short-range Radar (SRR). LRR systems can be used, for example, to detect objects that are farther away (e.g., 200 meters, 300 meters) from the vehicle transmitting the signal. LRR systems can operate in the 77 GHz band (e.g., 76-81 GHz). SRR systems can be used, for example, for blind spot detection or collision avoidance. SRR systems can operate in the 24 GHz band. MRR systems can operate in either the 24 GHz band or the 77 GHz band. Other frequency bands can also be supported.

Autonomous vehicle **102** can further include an internal computing system **124** that can interact with sensor systems **108** as well as the mechanical systems (e.g., vehicle propulsion system **114**, braking system **116**, steering system **118**, cabin system **120** and safety system **122**). Internal computing system **124** includes at least one processor and at least one memory system that can store executable instructions to be executed by the processor. Internal computing system **124** can include any number of computing subsystems that can function to control autonomous vehicle **102**. Internal computing system **124** can receive inputs from passengers and/or human drivers within autonomous vehicle **102**.

Internal computing system **124** can include control service **126**, which functions to control operation of autonomous vehicle **102** via, for example, the mechanical systems as well as interacting with sensor systems **108**. Control service **126** can interact with other systems (e.g., constraint service **128**, communication service **130**, latency service **132**, and internal computing system **124**) to control operation of autonomous vehicle **102**.

Internal computing system **124** can also include constraint service **128**, which functions to control operation of autonomous vehicle **102** through application of rule-based restrictions or other constraints on operation of autonomous vehicle **102**. Constraint service **128** can interact with other systems (e.g., control service **126**, communication service **130**, latency service **132**, user interface service **134**) to control operation of autonomous vehicle **102**.

Internal computing system **124** can further include communication service **130**, which functions to control transmission of signals from, and receipt of signals by, autonomous vehicle **102**. Communication service **130** can interact with safety system **122** to provide the waveform sensing, amplification, and repeating functionality described herein. Communication service **130** can interact with other systems (e.g., control service **126**, constraint service **128**, latency service **132** and user interface service **134**) to control operation of autonomous vehicle **102**.

Internal computing system **124** can also include latency service **132**, which functions to provide and/or utilize timestamp information on communications to help manage and coordinate time-sensitive operations within internal computing system **124** and autonomous vehicle **102**. Thus, latency service **132** can interact with other systems (e.g., control service **126**, constraint service **128**, communication service **130**, user interface service **134**) to control operation of autonomous vehicle **102**.

Internal computing system **124** can further include user interface service **134**, which functions to provide information to, and receive inputs from, human passengers within autonomous vehicle **102**. This can include, for example, receiving a desired destination for one or more passengers and providing status and timing information with respect to arrival at the desired destination. User interface service **134** can interact with other systems (e.g., control service **126**, constraint service **128**, communication service **130**, latency service **132**) to control operation of autonomous vehicle **102**.

Internal computing system **124** can function to send and receive signals from autonomous vehicle **102** regarding reporting data for training and evaluating machine learning algorithms, requesting assistance from a remote computing system **150** in FIG. **1**B or a human operator, software updates, rideshare information (e.g., pickup and/or dropoff requests and/or locations), etc.

The remote computing system **150**, as illustrated in FIG. 1B, is configured to send/receive a signal from the autonomous vehicle **102** regarding reporting data for training and evaluating machine learning algorithms, requesting assistance from remote computing system **150** or a human operator via the remote computing system **150**, software service updates, rideshare pickup and drop off instructions, etc.

The remote computing system **150** includes an analysis service **152** that is configured to receive data from autonomous vehicle **102** and analyze the data to train or evaluate machine learning algorithms for operating the autonomous vehicle **102** such as performing object detection for methods and systems disclosed herein. The analysis service **152** can also perform analysis pertaining to data associated with one or more errors or constraints reported by autonomous vehicle **102**. In another example, the analysis service **152** is located within the internal computing system **124**.

The remote computing system **150** can also include a user interface service **154** configured to present metrics, video, pictures, sounds reported from the autonomous vehicle **102** to an operator of remote computing system **150**. User interface service **154** can further receive input instructions from an operator that can be sent to the autonomous vehicle **102**.

The remote computing system **150** can also include an instruction service **156** for sending instructions regarding the operation of the autonomous vehicle **102**. For example, in response to an output of the analysis service **152** or user interface service **154**, instructions service **156** can prepare instructions to one or more services of the autonomous vehicle **102** or a co-pilot or passenger of the autonomous vehicle **102**.

The remote computing system **150** can also include a rideshare service **158** configured to interact with ridesharing applications **140** operating on (potential) passenger computing devices. The rideshare service **158** can receive requests to be picked up or dropped off from passenger ridesharing app **140** and can dispatch autonomous vehicle **102** for the trip. The rideshare service **158** can also act as an intermediary between the ridesharing app **140** and the autonomous vehicle wherein a passenger might provide instructions to the autonomous vehicle to **102** go around an obstacle, change routes, honk the horn, etc.

FIG. **1**C illustrates an example autonomous vehicle **160** in accordance with one embodiment. In one embodiment, autonomous vehicle **160** is the same as autonomous vehicle **102** described with respect to FIGS. **1**A and **1**B. The autonomous vehicle **160** can navigate about roadways without a human driver based upon sensor signals output by sensor systems **162-164** of the autonomous vehicle **160**. The autonomous vehicle **160** includes a plurality of sensor systems **162-164** (a first sensor system **162** through an Nth sensor system **164**). The sensor systems **162-164** are of different types and are arranged about the autonomous vehicle **160**. For example, the first sensor system **162** may be a camera sensor system and the Nth sensor system **164** may be a lidar sensor system. Other example sensor systems include, but are not limited to, radar sensor systems, global positioning system (GPS) sensor systems, inertial measurement units (IMU), infrared sensor systems, laser sensor systems, sonar sensor systems, and the like. Furthermore, some or all of the of sensor systems **162-164** may be articulating sensors that can be oriented/rotated such that a field of view of the articulating sensors is directed towards different regions surrounding the autonomous vehicle **160**.

The autonomous vehicle **160** further includes several mechanical systems that can be used to effectuate appropriate motion of the autonomous vehicle **160**. For instance, the mechanical systems **190** can include but are not limited to, a vehicle propulsion system **192**, a braking system **194**, and a steering system **196**. The vehicle propulsion system **192** may include an electric motor, an internal combustion engine, or both. The braking system **194** can include an engine break, brake pads, actuators, and/or any other suitable componentry that is configured to assist in decelerating the autonomous vehicle **160**. The steering system **196** includes suitable componentry that is configured to control the direction of movement of the autonomous vehicle **160** during propulsion.

The autonomous vehicle **160** additionally includes a chassis controller **182** that is activated to manipulate the mechanical systems **190** when an activation threshold of the chassis controller **182** is reached.

The autonomous vehicle **160** further comprises a computing system **170** that is in communication with the sensor systems **162-164**, the mechanical systems **190**, and the chassis controller **182**. While the chassis controller **182** is activated independently from operations of the computing system **170**, the chassis controller **182** may be configured to communicate with the computing system **170**, for example, via a controller area network (CAN) bus **184**. The computing system **170** includes a processor **172** and memory **174** that stores instructions which are executed by the processor **172** to cause the processor **172** to perform acts in accordance with the instructions.

The memory **174** comprises a detection system **176**, a path planning system **178**, and a control system **180**. The detection system **176** identifies objects in the vicinity (e.g., scene context) of the autonomous vehicle **160**. The detection system **176** may analyze sensor signals generated by the sensor system **162-164** to identify the objects. Detection system **176** may also identify characteristics of the detected objects, such as distance, velocity, direction, and so on. In some embodiments, the detection system **176** implements one or more trained machine learning (ML) models for the object identification.

The path planning system **178** generates a path plan for the autonomous vehicle **160**, wherein the path plan can be identified both spatially and temporally according to one or more impending timesteps. The path plan can include one or more maneuvers to be performed by the autonomous vehicle **160**. In one embodiment, the path planning system **178** can respond to detected EMVs in accordance with the techniques discussed herein.

The control system **180** is configured to control the mechanical systems of the autonomous vehicle **160** (e.g., the vehicle propulsion system **192**, the braking system **194**, and the steering system **196** based upon an output from the sensor systems **162-164** and/or the path planning system **178**. For instance, the mechanical systems can be controlled by the control system **180** to execute the path plan determined by the path planning system **178**. Additionally or alternatively, the control system **180** may control the mechanical systems **192-196** to navigate the autonomous vehicle **160** in accordance with outputs received from the sensor systems **162-164**.

In some examples described herein autonomous vehicle **102** or **160** (or another device) may be described as collecting data corresponding to surrounding vehicles. This data may be collected without associated identifiable information from these surrounding vehicles (e.g., without license plate numbers, make, model, and the color of the surrounding vehicles). Accordingly, the techniques mentioned here can because for the beneficial purposes described, but without the need to store potentially sensitive information of the surrounding vehicles.

In some examples described herein autonomous vehicle **102** or **160** (or another device) may be described as collecting data corresponding to surrounding vehicles. This data may be collected without associated identifiable information from these surrounding vehicles (e.g., without license plate numbers, make, model, and the color of the surrounding vehicles). Accordingly, the techniques mentioned here can because for the beneficial purposes described, but without the need to store potentially sensitive information of the surrounding vehicles.

In some examples, the autonomous vehicle includes radar microDoppler holography operation to combine data received at multiple sensors that are located in different locations, thereby enabling the use of additional microDoppler information collected at varying angles from a target.

FIG. **2** illustrates Radar sensor operation for microDoppler detection, according to some embodiments. Sensors **205** within an autonomous vehicle **200** includes multiple radar sensors, including at least a first radar sensor at a first location **210** and a second radar sensor at a second, different location **215**, wherein the first and second Radar sensors **210-215** have overlapping fields of view. The autonomous vehicle further includes one or more Radar transmitters **217** to generate and transmit Radar signals **220**. The sensors **205** may be utilized to detect and identify objects, including target object **240**.

In operation, the autonomous vehicle generates and transmits the Radar signals **220** comprising radio signals in one or more established frequency ranges for Radar. The Radar sensors **210-215** each detect reflected radar signals **225** from objects that are within range, which may include the illustrated target object **240**, which may include any person, animal, or inanimate object. Certain objects may be in motion, illustrated as the motion vector **250** in a certain direction for the target object **240**, resulting in a Doppler shift in the reflected Radar signals **225**. Further, the target object **240** may include a vibration or rotation component **255**, resulting in a micro-Doppler effect that may be applied in identifying the target object **240**. However, a vibration or rotation component **255** may in a direction other than a radial direction **260**.

In some embodiments, the autonomous vehicle **200** includes a processing unit that provides multi-sensor Radar microDoppler holography to enable detection of microDoppler effects that are not limited to a radial direction from a Radar sensor. A system includes applies microDoppler signatures from different sensors at different locations, and provides for coherently combining the phase information from the different radar sensors to generate microDoppler motion vectors of the different point cloud vectors.

In some examples, during sensor calibration, the orientation and location of the different radar sensors **210-215** with overlapping field of views are recorded in the main Radar processing unit. A phase conversion map is derived based on the relative locations of the sensors with the vehicle platform datum. This map is derived via a mathematical model based on Erdely's principle.

In some embodiments, a system provides for comprehensive motion data reporting. Because information from overlapping Radar sensors is used to perform the point cloud generation, the information from the available target views is used, and it is not restricted to the radial direction only. This results in a higher sensitivity to motion patterns and an information rich point cloud.

Further, a system can enable low latency in operation. In some embodiments, the point cloud formation process is based on the use of two computationally efficient algorithms, the Fast Fourier Transform (FFT) and the Discrete Wavelet Transform (DWT). By performing the phase compensation map design as an offline process, a system or process has the potential to achieve low latency outputs due to the efficiency of its algorithmic core.

Because the phase compensation map was designed using mathematical procedures capable of generating closed form expressions, the reconstruction process has a deterministic behavior that allows process to evaluate its performance in the design stage. This stands in contrast to artificial intelligence (AI) or kernel related point cloud formation methods that require extensive validation to tune their performance parameters.

FIG. **3** is an illustration of multi-sensor radar microDoppler holography, according to some embodiments. In a system **300**, such as an autonomous vehicle system, sensor data **305** is collected, where the sensor data includes Radar sensor data. In particular, multiple raw Radar sensor data sets **310** are generated for processing. In some embodiments, rather than being limited to processing of Radar data received at a signal location, the system **300** includes processing Radar data from multiple locations. As further illustrated in FIG. **4**, in order to allow effective use of Radar data collected at multiple locations, the processing of Radar data **330** includes application of a Fast Fourier Transform (FFT) calculation and Discrete Wave Transform (DWT) calculation, and application of phase compensation to allow addition of the processed Radar data. The system further provides for micro-Doppler and Doppler information extraction from the processed Radar data **335** for use in forming a Radar point cloud **340**.

The generated Radar point cloud **340** may then be provided to a perception stack **345** in the system **300**, which may then provide perception information for use in autonomous vehicle operation **350**. The perception stack **345**, described at a high level, involves the use of sensor data, such as sensor data **305**, to perceive what is present and what is occurring around an autonomous vehicle, such as autonomous vehicle **102** illustrated in FIGS. **1**A and **1**B. The perception stack **345** is used to enable the autonomous vehicle to detect the surrounding environment using information including data from the sensor systems and other components of the autonomous vehicle. More specifically, the perception stack **345** may be utilized to detect and classify objects, and determine locations, velocities, directions, and other information regarding such objects, which then may be utilized in the operation of the autonomous vehicle.

FIG. **4** illustrates multi-sensor Radar data processing, according to some embodiments. As illustrated in FIG. **4**, raw Radar sensor data **410** from multiple sensors at different locations, such as data received from sensors **104** of an autonomous vehicle **102**, may be received by a processing unit **420**, the processing unit **420** including a processing chain to provide processing and addition of the Radar and data. In the processing unit **420**, a 2D (two-dimensional) Fourier transform **422** of the raw Radar sensor data **410** is calculated to generate Doppler spatial frequency maps **426**.

In some embodiments, the processing unit **420** calculates a Discrete Wavelet Transform (DWT) in the Doppler direction (i.e., in the direction of the vector **250** as illustrated in FIG. **2**) to generate sensor data transforms. Further, based on a location of each Radar sensor, a phase compensation is applied to each sensor data transform. The phase compensation may be based upon a phase compensation map **430**, which may be generated prior to the operation of the Radar processing unit **420**. The resulting phase compensated data transforms are then added together **444**. An inverse 2D FFT **450** of the sum of the compensated data transforms is calculated in the Range-Azimuth direction to generate a transform result. As illustrated, the processing includes DWT microDoppler information extraction **452** to extract microDoppler information and DWT Doppler information extraction **454** to extract Doppler information. In the processing, low wavelet scales main components are identified and extracted using adaptive thresholding, with this value being reported as the main radial velocity component. Further, high wavelet scales main components are extracted from the discarded information in the adaptive thresholding, and this information is reported as the vibrational and rotational motion vectors.

The results of inverse 2D FFT calculation **450**, DWT microDoppler information extraction **452**, and DWT Doppler information extraction **454** are provided to CFAR (Constant False Alarm Rate) filtering **456** to eliminate clutter responses. CFAR in general refers to an adaptive algorithm for detecting target signal reflections in the presence of background noise, clutter, and interference. The resulting Radar point cloud is then formed **458**.

The resulting Radar point cloud may then be reported to the perception stack **460** for perception processing, and use in, for example, autonomous vehicle operation.

FIG. **5** is a flowchart to illustrate a process for multi-sensor radar microDoppler holography, according to some embodiments. In some embodiments, a process **500** includes generation and transmission of Radar signals in operation of a system **505**, wherein the system may include an autonomous vehicle system. Reflected Radar signals are then respectively by multiple Radar sensors located in multiple locations **510**, wherein the reflected Radar signals may be signals reflected by one or more objects in the vicinity of the system. Multiple Raw Radar signal data sets are generated from the received reflected signals at the multiple Radar sensors **515**. The one or more objects may include a velocity relative to the system, thus generating a Doppler effect, and may have vibration or rotation qualities, thus generating a micro-Doppler effect. Doppler effect and micro-Doppler effect qualities thus may be contained in the reflected Radar data.

In some embodiments, the process **500** further includes generating a phase compensation map **520**, and performing processing and addition of the multiple Radar data **525**. The processing, as further illustrated in FIG. **6**, may include application of a Fast Fourier Transform (FFT) calculation and Discrete Wave Transform (DWT) calculation, and application of phase compensation (utilizing the phase compensation map) to allow addition of the processed Radar data. The system further provides for micro-Doppler and Doppler information extraction from the processed Radar data for use in populating a Radar point cloud output including micro-Doppler information **530**.

The generated output is directed to a perception stack of the system **535**, and the perception stack generates a perception result based at least in part on the Radar micro-Doppler output **540**. The process **500** may further provide for performing a control operation for the system, such as a control operation for an autonomous vehicle system, utilizing the perception result **545**.

FIG. **6** is a flowchart to illustrate a process for multiple Radar sensor data processing, according to some embodiments. In some embodiments, a process **600** includes receiving raw Radar sensor data from multiple Radar sensors at multiple locations **605**, such as data received from sensors **104** of an autonomous vehicle **102** as illustrated in FIGS. **1**A and **1**B. A 2D Fourier transform is performed on the raw Radar sensor data sets to generate Doppler spatial frequency maps **610**.

The process **600** further includes performing a DWT calculations on the Radar spatial frequency maps in the Doppler direction to generate sensor data transforms **615**. Phase compensation is performed using a phase compensation map (such as the phase compensation map generated in block **520** of FIG. **5**) to generate phase compensated data transforms **620**. The phase compensated data transforms are then added together to generate a sum **625**. An inverse 2D Fourier transform of the sum of the compensated data transforms is calculated in the Range-Azimuth direction **630**.

The process **600** further includes performing a DWT processing includes performing DWT microDoppler information extraction and DWT Doppler information extraction **635**. The results of inverse 2D Fourier calculation, DWT microDoppler information extraction, and DWT Doppler information extraction are provided to CFAR (Constant False Alarm Rate) filtering **640**. The results of the CFAR filtering are then applied in population of the Radar point cloud **645**.

The resulting Radar point cloud is reported to the perception stack for perception processing **650**.

FIG. **7** illustrates an embodiment of an exemplary computing architecture for multi-sensor radar microDoppler holography, according to some embodiments. In various embodiments as described above, a computing architecture **700** may comprise or be implemented as part of an electronic device. In some embodiments, the computing architecture **700** may be representative, for example, of a computer system that implements one or more components of the operating environments described above. The computing architecture **700** may be utilized to provide multi-sensor radar microDoppler holography, such as described in FIGS. **1**A-**6**.

As used in this application, the terms "system" and "component" and "module" are intended to refer to a computer-related entity, either hardware, a combination of hardware and software, software, or software in execution, examples of which are provided by the exemplary computing architecture **700**. For example, a component can be, but is not limited to being, a process running on a processor, a processor, a hard disk drive or solid-state drive (SSD), multiple storage drives (of optical and/or magnetic storage medium), an object, an executable, a thread of execution, a program, and/or a computer. A storage medium may include a non-transitory storage medium. By way of illustration, both an application running on a server and the server can be a component. One or more components can reside within a process and/or thread of execution, and a component can be localized on one computer and/or distributed between two or more computers. Further, components may be communicatively coupled to each other by various types of communications media to coordinate operations. The coordination may involve the unidirectional or bi-directional exchange of information. For instance, the components may communicate information in the form of signals communicated over the communications media. The information can be implemented as signals allocated to various signal lines. In such allocations, each message is a signal. Further embodiments, however, may alternatively employ data messages. Such data messages may be sent across various connections. Exemplary connections include parallel interfaces, serial interfaces, and bus interfaces.

The computing architecture **700** includes various common computing elements, such as one or more processors, multi-core processors, co-processors, memory units, chipsets, controllers, peripherals, interfaces, oscillators, timing devices, video cards, audio cards, multimedia input/output (I/O) components, power supplies, and so forth. The embodiments, however, are not limited to implementation by the computing architecture **700**.

As shown in FIG. **7**, the computing architecture **700** includes one or more processors **702** and one or more graphics processors **708**, and may be a single processor desktop system, a multiprocessor workstation system, or a server system having a large number of processors **702** or processor cores **707**. In one embodiment, the system **700** is a processing platform incorporated within a system-on-a-chip (SoC or SOC) integrated circuit for use in mobile, handheld, or embedded devices.

An embodiment of system **700** can include, or be incorporated within, a server-based gaming platform, a game console, including a game and media console, a mobile gaming console, a handheld game console, or an online game console. In some embodiments system **700** is a mobile phone, smart phone, tablet computing device or mobile Internet device. Data processing system **700** can also include, couple with, or be integrated within a wearable device, such as a smart watch wearable device, smart eyewear device, augmented reality device, or virtual reality device. In some embodiments, data processing system **700** is a television or set top box device having one or more processors **702** and a graphical interface generated by one or more graphics processors **708**.

In some embodiments, the one or more processors **702** each include one or more processor cores **707** to process instructions which, when executed, perform operations for system and user software. In some embodiments, each of the one or more processor cores **707** is configured to process a specific instruction set **709**. In some embodiments, instruction set **709** may facilitate Complex Instruction Set Computing (CISC), Reduced Instruction Set Computing (RISC), or computing via a Very Long Instruction Word (VLIW). Multiple processor cores **707** may each process a different instruction set **709**, which may include instructions to facilitate the emulation of other instruction sets. Processor core **707** may also include other processing devices, such a Digital Signal Processor (DSP).

In some embodiments, the processor **702** includes cache memory **704**. Depending on the architecture, the processor **702** can have a single internal cache or multiple levels of internal cache. In some embodiments, the cache memory **704** is shared among various components of the processor **702**. In some embodiments, the processor **702** also uses an external cache (e.g., a Level-3 (L3) cache or Last Level Cache (LLC)) (not shown), which may be shared among processor cores **707** using known cache coherency techniques. A register file **706** is additionally included in processor **702** which may include different types of registers for storing different types of data (e.g., integer registers, floating point registers, status registers, and an instruction pointer register). Some registers may be general-purpose registers, while other registers may be specific to the design of the processor **702**.

In some embodiments, one or more processor(s) **702** are coupled with one or more interface bus(es) **710** to transmit communication signals such as address, data, or control signals between processor **702** and other components in the system. The interface bus **710**, in one embodiment, can be a processor bus, such as a version of the Direct Media Interface (DMI) bus. However, processor buses are not limited to the DMI bus, and may include one or more Peripheral Component Interconnect buses (e.g., PCI, PCI Express), memory buses, or other types of interface buses. In one embodiment the processor(s) **702** include an integrated memory controller **716** and a platform controller hub **730**. The memory controller **716** facilitates communication between a memory device and other components of the system **700**, while the platform controller hub (PCH) **730** provides connections to I/O devices via a local I/O bus.

Memory device **720** can be a dynamic random-access memory (DRAM) device, a static random-access memory (SRAM) device, non-volatile memory device such as flash memory device or phase-change memory device, or some other memory device having suitable performance to serve as process memory. Memory device **720** may further include non-volatile memory elements for storage of firmware. In one embodiment the memory device **720** can operate as system memory for the system **700**, to store data **722** and instructions **721** for use when the one or more processors **702** execute an application or process. Memory controller hub **716** also couples with an optional external graphics processor **712**, which may communicate with the one or more graphics processors **708** in processors **702** to perform graphics and media operations. In some embodiments a display device **711** can connect to the processor(s) **702**. The display device **711** can be one or more of an internal display device, as in a mobile electronic device or a laptop device, or an external display device attached via a display interface (e.g., DisplayPort, etc.). In one embodiment the display device **711** can be a head mounted display (HMD) such as a stereoscopic display device for use in virtual reality (VR) applications or augmented reality (AR) applications.

In some embodiments the platform controller hub **730** enables peripherals to connect to memory device **720** and processor **702** via a high-speed I/O bus. The I/O peripherals include, but are not limited to, an audio controller **746**, a network controller **734**, a firmware interface **728**, a wireless transceiver **726**, touch sensors **725**, a data storage device **724** (e.g., hard disk drive, flash memory, etc.). The data storage device **724** can connect via a storage interface (e.g., SATA) or via a peripheral bus, such as a Peripheral Component Interconnect bus (e.g., PCI, PCI Express). The touch sensors **725** can include touch screen sensors, pressure sensors, or fingerprint sensors. The wireless transceiver **726** can be a Wi-Fi transceiver, a Bluetooth transceiver, or a mobile network transceiver such as a 3G, 4G, Long Term Evolution (LTE), or 5G transceiver. The firmware interface **728** enables communication with system firmware, and can be, for example, a unified extensible firmware interface (UEFI). The network controller **734** can enable a network connection to a wired network. In some embodiments, a high-performance network controller (not shown) couples with the interface bus **710**. The audio controller **746**, in one embodiment, is a multi-channel high-definition audio controller. In one embodiment the system **700** includes an optional legacy I/O controller **740** for coupling legacy (e.g., Personal System 2 (PS/2)) devices to the system. The platform controller hub **730** can also connect to one or more Universal Serial Bus (USB) controllers **742** connect input devices, such as keyboard and mouse **743** combinations, a camera **744**, or other USB input devices.

In the description above, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the described embodiments. It will be apparent, however, to one skilled in the art that embodiments may be practiced without some of these specific details. In other instances, well-known structures and devices are shown in block diagram form. There may be intermediate structure between illustrated components. The components described or illustrated herein may have additional inputs or outputs that are not illustrated or described.

Various embodiments may include various processes. These processes may be performed by hardware components or may be embodied in computer program or machine-executable instructions, which may be used to cause a general-purpose or special-purpose processor or logic circuits programmed with the instructions to perform the processes. Alternatively, the processes may be performed by a combination of hardware and software.

Portions of various embodiments may be provided as a computer program product, which may include a computer-readable medium having stored thereon computer program instructions, which may be used to program a computer (or other electronic devices) for execution by one or more processors to perform a process according to certain embodiments. The computer-readable medium may include, but is not limited to, magnetic disks, optical disks, read-only memory (ROM), random access memory (RAM), erasable programmable read-only memory (EPROM), electrically-erasable programmable read-only memory (EEPROM), magnetic or optical cards, flash memory, or other type of computer-readable medium suitable for storing electronic instructions. Moreover, embodiments may also be downloaded as a computer program product, wherein the program may be transferred from a remote computer to a requesting computer.

Many of the methods are described in their most basic form, but processes can be added to or deleted from any of the methods and information can be added or subtracted from any of the described messages without departing from the basic scope of the present embodiments. It will be apparent to those skilled in the art that many further modifications and adaptations can be made. The particular embodiments are not provided to limit the concept but to illustrate it. The scope of the embodiments is not to be determined by the specific examples provided above but only by the claims below.

If it is said that an element "A" is coupled to or with element "B," element A may be directly coupled to element B or be indirectly coupled through, for example, element C. When the specification or claims state that a component, feature, structure, process, or characteristic A "causes" a component, feature, structure, process, or characteristic B, it means that "A" is at least a partial cause of "B" but that there may also be at least one other component, feature, structure, process, or characteristic that assists in causing "B." If the specification indicates that a component, feature, structure, process, or characteristic "may", "might", or "could" be included, that particular component, feature, structure, process, or characteristic is not required to be included. If the specification or claim refers to "a" or "an" element, this does not mean there is only one of the described elements.

An embodiment is an implementation or example. Reference in the specification to "an embodiment," "one embodiment," "some embodiments," or "other embodiments" means that a particular feature, structure, or characteristic described in connection with the embodiments is included in at least some embodiments, but not necessarily all embodiments. The various appearances of "an embodiment," "one embodiment," or "some embodiments" are not necessarily all referring to the same embodiments. It should be appreciated that in the foregoing description of exemplary embodiments, various features are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various novel aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed embodiments requires more features than are expressly recited in each claim. Rather, as the following claims reflect, novel aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims are hereby expressly incorporated into this description, with each claim standing on its own as a separate embodiment.

The foregoing description and drawings are to be regarded in an illustrative rather than a restrictive sense. Persons skilled in the art will understand that various modifications and changes may be made to the embodiments described herein without departing from the broader spirit and scope of the features set forth in the appended claims.

What is claimed is:

1. An apparatus comprising:

a plurality of Radar sensors, including at least a first Radar sensor at a first location and a second Radar sensor at a second location, the first Radar sensor and the second Radar sensor having overlapping fields of view; and

a processing chain for processing of sensor data, the processing chain to:

perform a two-dimensional (2D) Fourier transform calculation for a plurality of sets of raw Radar sensor data to generate Doppler spatial frequency map data, the plurality of sets of raw Radar sensor data including at least a first set of raw sensor data associated with the first Radar sensor at the first location and a second set of raw sensor data associated with the second Radar sensor at the second, different location;

perform a Discrete Wavelet Transform (DWT) calculation of the Doppler spatial frequency map data to generate sensor data transforms;

apply phase compensation to generate phase compensated data transforms;

add the phase compensated data transforms to generate a sum of the phase compensated data transforms;

perform an inverse 2D Fourier transform calculation in a Range-Azimuth direction to generate a transform result; and

extract microDoppler information and Doppler information extraction from the transform result.

2. The apparatus of claim **1**, wherein applying phase compensation includes applying phase compensation based on a generated phase compensation map.

3. The apparatus of claim **1**, wherein the processing chain is further to:

perform CFAR (Constant False Alarm Rate) filtering of the transform result and the extracted microDoppler information and Doppler information.

4. The apparatus of claim **1**, wherein the processing chain is further to:

generate a Radar point cloud utilizing the transform result and the extracted microDoppler information and Doppler information.

5. The apparatus of claim **4**, further comprising a perception stack, wherein the processing chain is further to provide the Radar point cloud to the perception stack to generate a perception result.

6. The apparatus of claim **5**, wherein the processing chain is further to:

perform a control operation for the apparatus based on the perception result.

7. The apparatus of claim **6**, wherein the apparatus is at least a portion of an autonomous vehicle.

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